ER = EPR for de Sitter

Tomonori Ugajin (Hakubi center, Kyoto)

Extreme universe annual meeting

Dec 27th, 2022

Based on

2104.13383 with Vijay Balasubramainian (Penn)

Arjun Kar (UBC)

2111.11688 with Akihiro Miyata (U.Tokyo → KITS)

+ W.I.P with Vijay Balasubramainian (Penn)

(Y. Nomura ?

E. Shaghoulian)

+ W.I.P with Shan Ming Ruan (YITP)

Rob Myers (Perimeter)

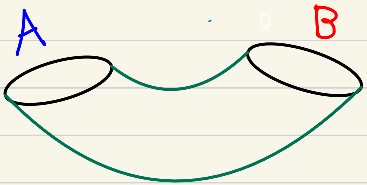
BH interior from quantum information

- The Goal of BOI group is to derive a consistent semi classical description of BH interior from quantum information theoretic point of view

- Such a description is particularly important for the physics of evaporating BH.

- This is because, a naive semi classical description of BH seems to contradict with unitarity of underlying quantum theory in the process

ER = EPR (Maldacena and Susskind)



Spatial worm hole
(Einstein Rosen bridge)

"Entanglement in gravity"

$\Downarrow$ geometric manifestation

Spatial worm hole

for an evaporating BH (A : BH microstates
B : Hawking quanta

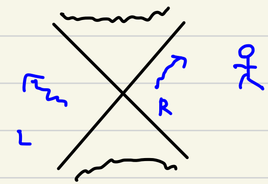
$\Rightarrow$ Indicates the existance of WH connecting BH and Hawking Rad

In this talk, I would like to explain the role of ER = EPR
worm hole for closed universe.

Information loss paradox (Entropy paradox)

- Evaporating BH + Hartle Hawking state (QFT state)

$$\boxed{|HH\rangle = \frac{1}{\sqrt{Z}} \sum_n e^{-\beta E_n/2} |E_n\rangle_{in} |E_n\rangle_{out}}$$



L: degrees of freedom in the BH interior

$T = \frac{1}{4M}$

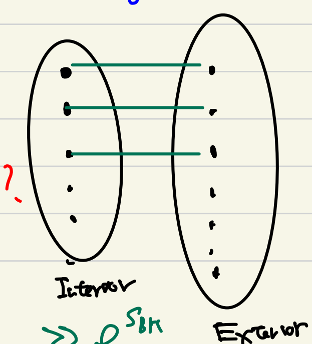
cf. $S(\rho_R) =$ # of Bell pairs shared by interior and exterior

- Due to the evaporation, $M \to 0$: $\beta \to 0$ $\quad S(\rho_R) = S_{th}(\beta)$ keeps increasing.

$\Rightarrow$ $\boxed{\text{Infinitely many states in the BH interior}}$ (locality of QFT)

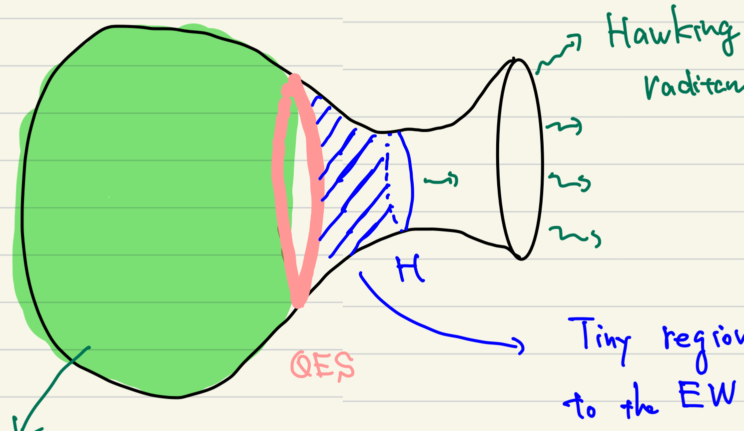
Contradiction?

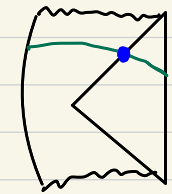
However $\boxed{S_{BH} \text{ counts \# of states in the BH interior}}$



Island regions in BH interiors

The entropy paradox is resolved if the island region in the BH interior belongs to radiation degrees of freedom





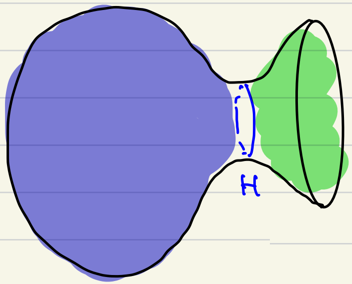
Tiny region corresponds to the EW of the black hole

Island region: Entanglement wedge of radiation

$\Rightarrow$ This structure naturally follows from AdS/CFT and HEE formula

• Comparison $\mathcal{H}_{BH} \otimes \mathcal{H}_{Rad}$ and an entangled state on it,

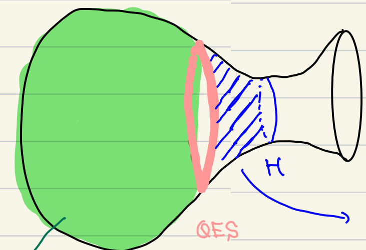
Usual idea

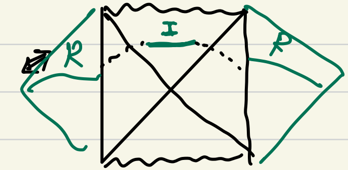


BH interior = EW of the BH

⇒ Contradicts with unitarity

The island formula





EW of the BH

EW of Hawking radiation

⇒ Consistent with unitarity

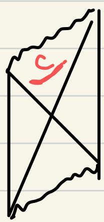
The island formula : The entropy of Hawking radiation is computed by the following formula

$$S(\rho_R) = \min_{I} \mathrm{Ext}\left[\frac{A[\partial I]}{4G} + S_{\text{bulk QFT}}[I \cup R] \right]$$

$S(\rho_R)$ computed in this way is consistent with

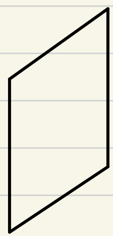
Entanglement between two disjoint Universes [Balasubramanian, Kar, TU]

A concise way to formulate the island formula is the following



universe A

gravitating



Universe B

$G = 0$

Non-gravitating

Consider two disjoint universes A and B

$\Rightarrow$ QFT Hilbert space $\mathcal{H}_{QFT,A} \otimes \mathcal{H}_{QFT,B}$

$(= CFT_{A,B})$

⊙ "TFD state"

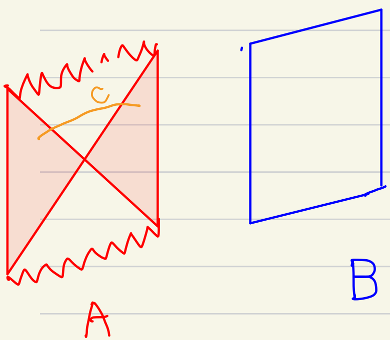
characterizes entanglement

$$|TFD\rangle_\beta = \frac{1}{\sqrt{Z(\beta)}} \sum_n e^{-\beta E_n/2} |i\rangle_A \otimes |\psi_i\rangle_B$$

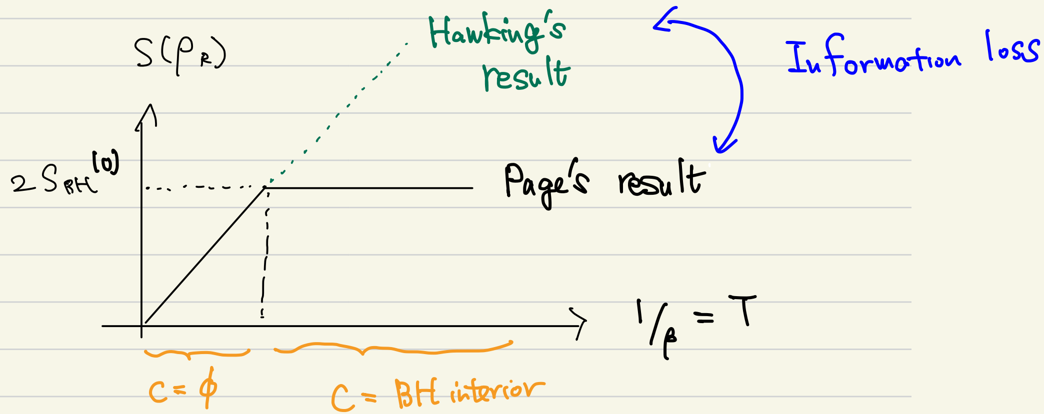
$$\in \mathcal{H}_{QFT,A} \otimes \mathcal{H}_{QFT,B}$$

$$\boxed{S_\beta(\rho_A) = \underset{C}{\mathrm{Min\,Ext}} \left[\frac{A[\partial C]}{4G_N} + S_{bulk,QFT}[A \cup C] \right]}$$

Resulting entropy is consistent with unitarity



$\Rightarrow$



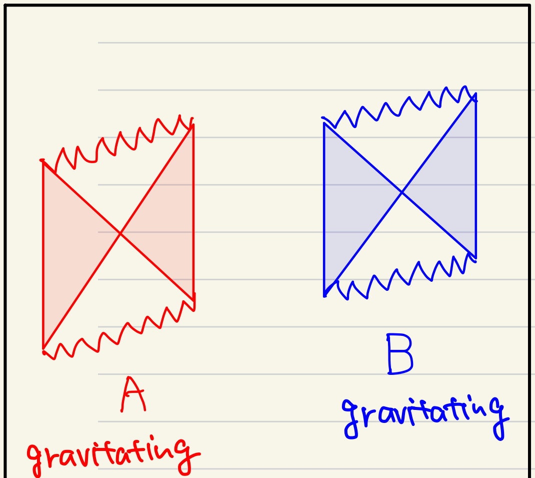
Where is the wormhole connecting BH and Hawking Rad ??

$\Rightarrow$ Invisible because turn off gravity on B (the universe for Hawking rad)

Entanglement between two gravitating universe

[Balasubramanian, Kar, TU]

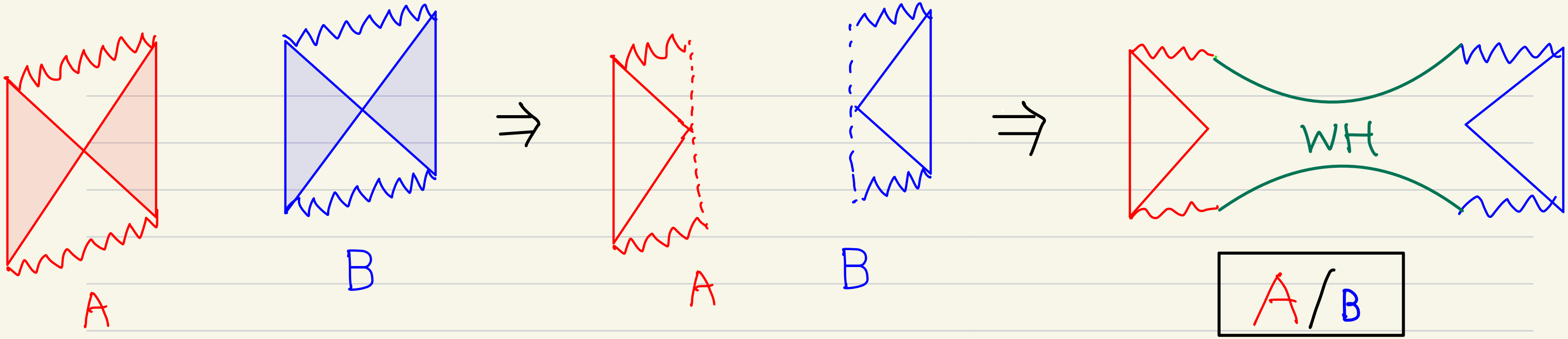
ER = EPR wormholes show up when we consider when both of the universes are gravitating



$$|TFD\rangle = \frac{1}{\sqrt{Z(\beta)}} \sum_n e^{-\beta E_i/2} |i\rangle_A \otimes |\psi_i\rangle_B$$

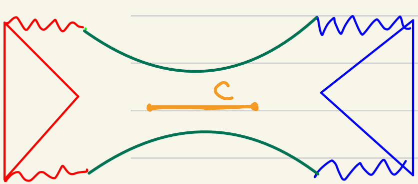
$$\in \mathcal{H}_{QFT,A} \otimes \mathcal{H}_{QFT,B}$$

$\Rightarrow$ The entanglement entropy is computed by the generalized entropy on the new spacetime constructed by suitably gluing A and B

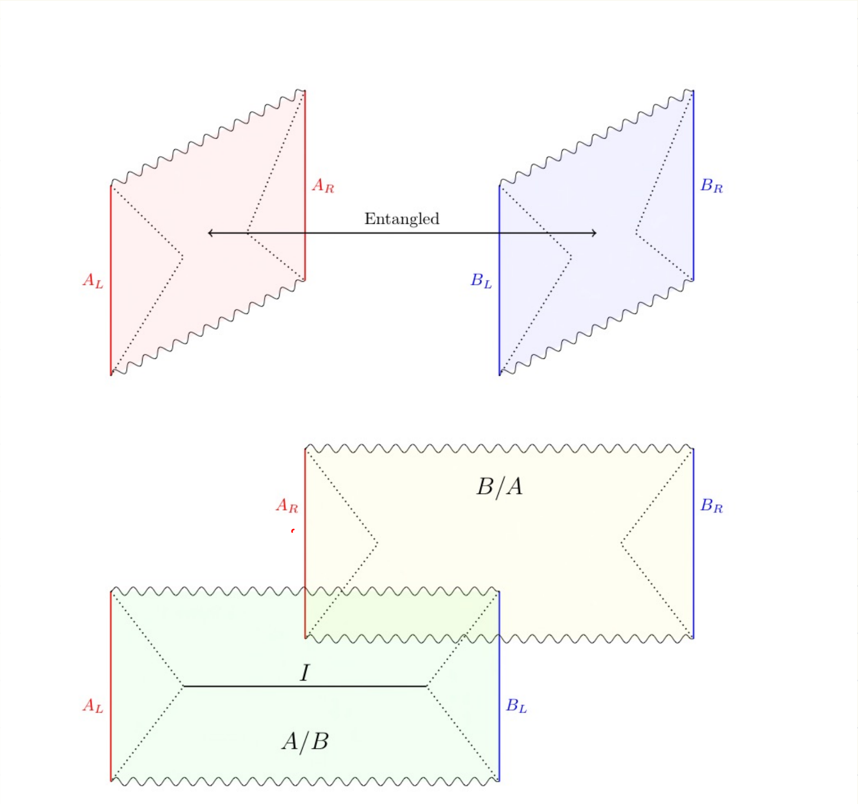


A/B is the solution of Einstein's eqs with the boundary condition
(Explicit calculations are possible in 2D JT gravity)

- Typically the resulting spacetime contains a long WH region connecting between the two horizon



$$\boxed{S(\rho_A) = \underset{c}{\mathrm{Min\,Ext}}\left[\frac{\mathrm{Area}^{A/B}}{4G}[\partial c] + S^{A/B}_{\mathrm{bulk\,QFT}}[c]\right]}$$

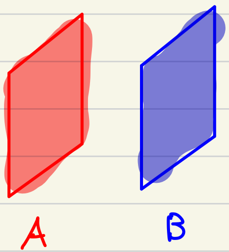


(Related study using SYK by Numasawa)

A doublely holographic set up [In progress with Myers and Ruan]

One can holographically study analogous system using 3D asymptotically AdS BH

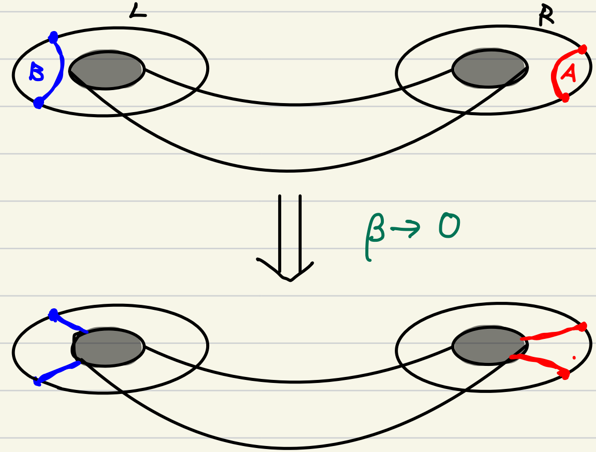
the Entangled state on



in 2D setup

Equivalent $\Longleftrightarrow$

$\boxed{\text{3D holographic description}}$ (Eternal BH with L-R boundaries)



(warm phase)

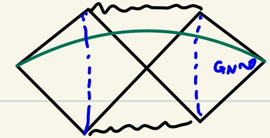
(Hot phase)

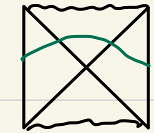
[Bachas...]

- Breaking $\mathbb{Z}_2$ symmetry : goes beyond AdS/BCFT.
- Both connected and disconnected phases are defined on BTZ
  $\Rightarrow$ different from Hawking - Page transition

$\boxed{\text{Applications to closed universe.}}$

The island formula for de Sitter





- We have been focusing on BHs in Asymptotically AdS or flat space where we have a weakly gravitating region for arbitary Cauchy slice

⇒ Validates the non-gravitating assumption ($G_N = 0$ in Hawking radiation)

⇒ ER = EPR worm hole plays a less role in these setup

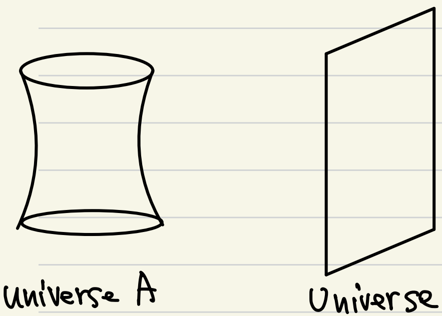
However for closed universe like de Sitter space, there is no weakly gravitating region for generic time slice

⇒ To study entanglement structure involving dS, We need to turn on gravity on both A and B

Naive island formula for dS

[Balasubramanian, Kar, TU]

see also [Maldacena et. al] [Hartman et al]



dS gravitating non gravitating

The same set up with the previous one by replacing AdS BH to dS

$$|TFD\rangle = \frac{1}{\sqrt{Z(\beta)}} \sum_n e^{-\beta E_i/2} |i\rangle_A \otimes |\psi_i\rangle_B$$

$$\in \mathcal{H}_{QFT,A} \otimes \mathcal{H}_{QFT,B}$$

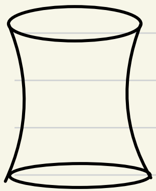
$\Rightarrow$ $S(\rho_A)$ is again computed by the island formula

But $S(\rho_A) = 0$ always... $\Rightarrow$ $\dim \mathcal{H}_{dS} = 1$??

Indeed the island region dS covers entire Cauchy slice.

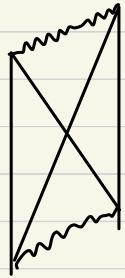
In the present work, We are studying entanglement between dS and AdS BH(

Entanglement between dS and gravitating universe



universe A

dS gravitating



Universe B

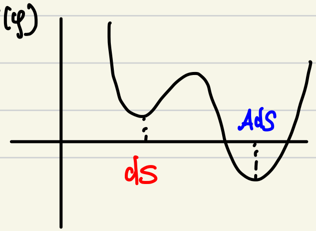
gravitating

Again we argue that the entropy is computed by the generalized entropy on constructed by gluing de Sitter and AdS BH

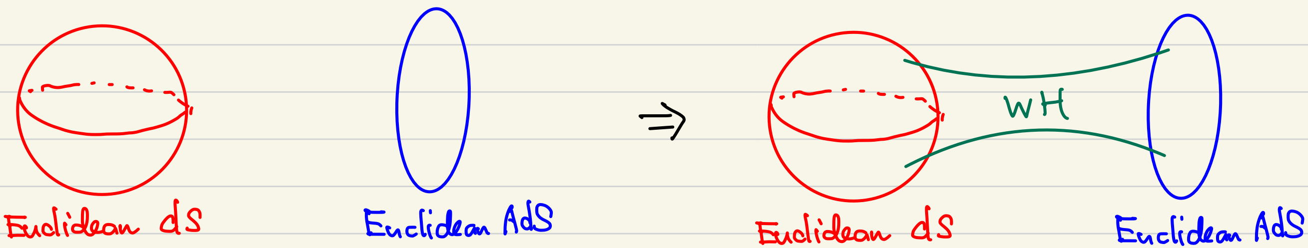
Recipi for A / B

(1) We start from a theory admitting both dS and AdS vacua

$$I = \int \sqrt{g}\left(R + (\partial\varphi)^2 - V(\varphi)\right)$$

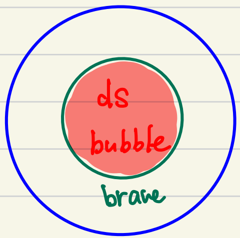


(2) The wormhole connecting these two can be regarded as a domain wall solution connecting two vacua



(3) when $\beta \to 0$ the domain wall gets thin and approximated by a brane

⇒ Use Israel's junction :

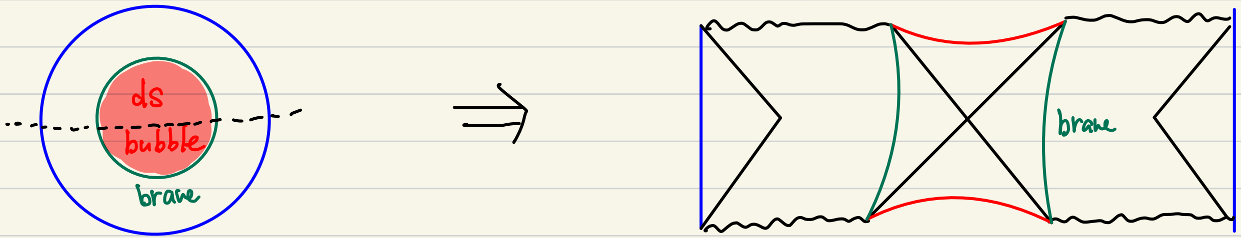


~ AdS BH with dS bubble inside.

details of the construction is involved even in JT [Mirbabayi]

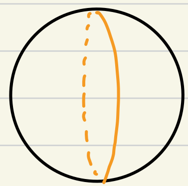
From Euclidean to Lorenzian

By continuing along the reflection symmetric slice we obtain the Lorenzian geometry.

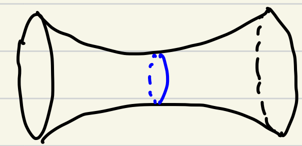


From Euclidean to Lorenzian

In order for such a geometry contain Cosmological horizon, we need $\boxed{S_{dS} > S_{AdS\,BH}}$

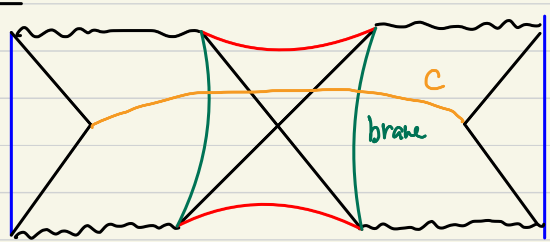


Cosmological horizon
: locally maximum



BH horizon
: locally minimum

QES



A / B

$S(\rho_A) \sim 2 S_{AdS\,BH}.$

$\Rightarrow$ Suggests $\mathcal{H}_{dS}$ is non-trivial because now $\mathcal{H}_{dS} \otimes \mathcal{H}_{AdS\,BH}$ when $S_{dS} > S_{AdS\,BH}$.

Relation to the result on vN algebra for dS

- It has been argued vN algebra for dS becomes nontrivial only when we include observer and its gravitational interaction with dS. [Pennington Witten ...]

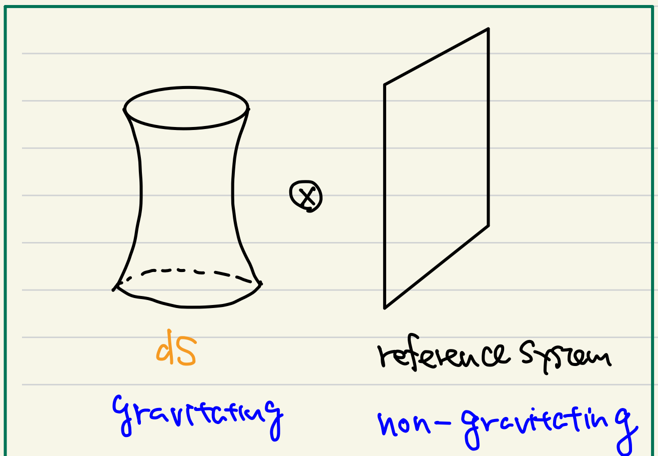
- In our case, AdS BH plays a role of observer.

- Perhaps this is the reason why we have non trival H_{ds} in this case.

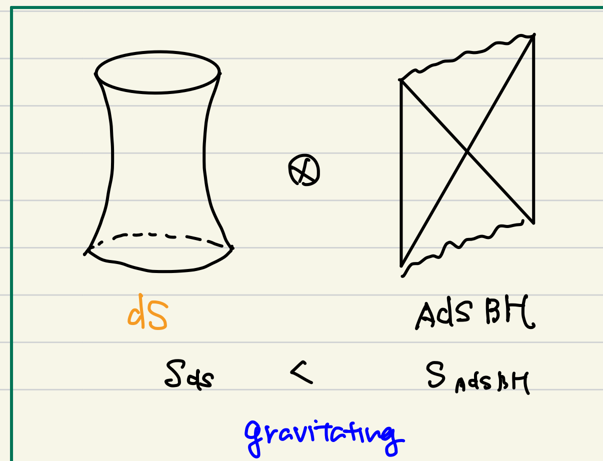
What happens for $S_{dS} < S_{AdS BH}$?

Glued geometry A/B still exists, but it does not contain cosmological horizon. $\Rightarrow$ $\mathcal{H}_{dS} \otimes \mathcal{H}_{AdS BH}$ is ill defined ?

$\Rightarrow$ Relation to dS entangled with reference system with ∞ dof
(Naive island formula)



$\sim$



Conclusion

- We study entanglement between d.o.f in closed universe and AdS BH.

- the Hilbert space of closed universe is fragile against entanglement with a larger Hilbert space.

Possible projects

(1) Quantum information theoretic description of de Sitter space

Microscopic model ?

(2) How do we get local semi classical description of BH interior ?

Do we need non-isometric code ? Is it natural from QI point of view ?

(3) Physics of baby universe and Quantum Error Correction.

(4) Challenging : Experimental realization of quantum BH ?

⇒ Recently developped notion of "Pseudo Random States"

seems promising.

Thank you!!